

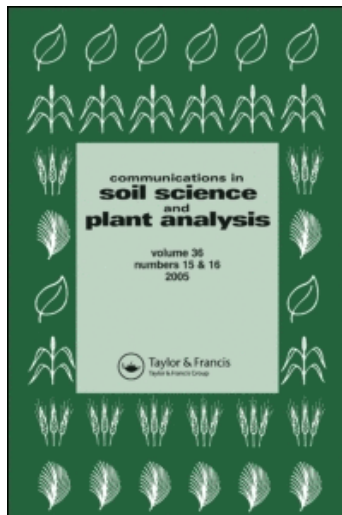
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Changes in Release Characteristics and Runoff Phosphorus for Soils Amended with Manure

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Changes in Release Characteristics and Runoff Phosphorus for Soils Amended with Manure

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Abstract: Application of manure on agricultural land can introduce considerable amounts of phosphorus (P) to natural water resources. The objectives of this study were to evaluate the effect of dairy manure application on 1) P released from surface soil by rainfall, 2) P removed from surface soil by runoff, and 3) soil P available for plants. A technique implementing a Soil Survey Laboratory method and USDA Runoff Model was applied on four Texas and three Utah soils. The application of manure (100 Mg/ha) considerably increased the amount of P released from the surface soil by rainfall, but there was no significant change in the pattern of P release (phosphorus release characteristics). Manure application increased both the runoff and available P for soils. For the Blanket soil (Texas), P released from surface soil by rainfall increased from 1.06 to 30.8 kg/ha/yr. The runoff P (kg/ha/yr) increased from 0.18 to 5.15 for fallow, from 0.16 to 4.71 for cropland, and from 0.13 to 3.88 for grassland. Soil P available for plants increased from 0.88, 0.90, and 0.93 to 25.7, 26.1, and 26.9 kg/ha/yr for fallow, cropland, and grassland, respectively. Similar effects of manure application were noticed for other Texas and Utah soils. The data suggest that manure could provide substantial amounts of available P for crop production in these soils. However, irrigated cropland amended annually with manure could contribute to nonpoint source pollution of surface freshwater bodies. The technique provides a tool to quantify the impact of manure application to agricultural land on water resources.

Keywords: Phosphorus release characteristics, anion exchange resin, runoff phosphorus, runoff equation, manure application

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INTRODUCTION

In 1997, livestock operations in the United States produced about 1 billion Mg of excreted animal wastes (manure), which contained approximately 1.73 million Mg P and 5.86 million Mg N (USDA 1997). The Council for Agricultural Science and Technology (1996) estimated that 42% of all P applications to crops in the United States could be supplied by manure. In recent decades, regular applications of animal manure on agricultural land became an attractive field practice for both nutrient and waste management programs.

When P added to agricultural land by manure and fertilizer applications exceeds P removal by harvested crops, repeated applications can lead to an accumulation in surface soils. Carpenter et al. (1998) reported that during the period of 1950–1995, an average P surplus of 26 kg/ha/yr accumulated on agricultural soils in the United States. Average soil test P levels in Wisconsin exceeded the levels required for optimum crop production because long-term P additions in manure and/or fertilizer have exceeded P removals in the harvested portion of crops (Bundy 1998). The accumulation increases the potential for P movement from soil through runoff and leaching to pollute surface and ground waters. Surface runoff from agricultural land is considered a major nonpoint P source of pollution for many lakes, rivers, estuaries, and coastal oceans (Carpenter et al. 1998).

Agronomic soil tests such as Olsen (Olsen et al. 1954), Bray1 (Bray and Kurtz 1945), and Mehlich3 (Mehlich 1984) have been used to estimate the effect of manure application on soil P and to investigate the relationship between P in surface soil and runoff water, but results have been inconsistent (Sharpley 1995; Pote et al. 1996; Sauer et al. 2000; Gaston et al. 2003). Another drawback is the inability of these tests to quantify P losses by runoff or measure changes in P release rate as a result of manure application on agricultural land.

The transport of soil P to surface waters depends on many factors including climate, soil type and hydrology, soil P content, agronomic practices, and landscape (Lemunyon and Gilbert 1993). Most of these factors were considered by the Soil Survey Laboratory technique (Elrashidi et al. 2003a) to estimate P release characteristics (PRC) and quantify runoff P for agricultural land. Application of the technique on 24 U.S. benchmark soils predicted runoff P ranging between 0.09 and 8.3 kg/ha/yr. The authors suggested that a runoff P threshold of 5.0 kg/ha/yr should raise awareness to a possible risk for near surface waters.

The objectives of this study were to investigate the effect of manure applications on P released from surface soil by rainfall, P removed by runoff water, and soil P available for plants. The study was conducted on four nonirrigated Texas soils and three irrigated Utah soils.

MATERIALS AND METHODS

Field Study and Soil Sampling

The study was conducted on seven soils in Texas and Utah. All four Texas soils (Malotterre, Windthorst, Blanket, and Purves) were sampled from fields in Erath County where the average rainfall is 809 mm/yr. The three Utah soils (Genola, Greenson, and Layton) were sampled from three different counties: Sanpete, Cache, and Weber, respectively, where the average rainfall is between 300 and 450 mm/yr. Alfalfa-barley/wheat and alfalfa-corn are the common crop rotations in the Utah counties. A supplemental surface irrigation is usually required during the growing season. Grass/pasture for cattle grazing is common in Erath County, and surface irrigation is not used.

In areas where intensive meat production and dairy cattle operations are present, crop and grassland receive regular applications of manure to supply essential nutrients and as a means of waste disposal. In this study, we applied the USDA runoff model (USDA 1991) to predict runoff water generated from soils under fallow, crop, and grass to evaluate the impact on surface waters.

Soil surveys were used to identify the key soil series and their locations in the study areas. In each field site, a test plot of approximately 25 acres (10 hectares) was selected. Dairy manure was applied two times during the fall of 1994 and 1995 on Texas sites. Application to Utah plots was carried out in the fall of 1998 and 1999. Manure produced in a local dairy operation was applied (100 Mg/ha) evenly by a mechanical spreader over one half of each plot area. The rest of the plot area was used as a control.

During spring following the second manure application, representative soil samples were collected from Ap1 horizon of manure and control plots of all seven soils. Samples were also collected from Ap2 horizon for Windthorst, Genola, and Greenson soil, and from both Ap2 and Ap3 horizons of Layton soil to investigate downward movement of manure P.

Soil Analysis

Soil samples were analyzed on air-dried less than 2-mm soil by methods described in Soil Survey Investigations Report (SSIR) No. 42 (Soil Survey Staff 1996). Alphanumeric codes in parentheses next to each method represent specific standard operating procedures. Particle size analysis was performed by sieve and pipette method (3A1). Total carbon (C) content was determined by dry combustion (6A2f), and CaCO_3 equivalent was estimated by electronic manometer method (6E1g). Organic C in soil was estimated from both the total-, and $\text{CaCO}_3\text{—C}$. Soil pH was measured in a 1:1 soil/water suspension (8C1f). Bulk density was determined on saran-coated clods method (4A1a). Classification and selected properties for soils are given in Table 1.

Table 1. Classification and selected characteristics for Texas and Utah surface and subsurface soils investigated

Soil (horizon)	Depth (CM)	Classification	Clay (%)	CaCO3 (%)	OC (%)	pH-water	BD (g/cc)
Maloterre (Ap)	0–20	Loamy-skeletal, carbonatic, thermic Lithic Ustochrept	33.2	22	3.03	7.8	1.40
Windthorst (Ap1)	0–15	Fine, mixed, thermic Udic Paleustalf	11.2	UD	0.81	5.4	1.51
Windthorst (Ap2)	15–28	Fine, mixed, thermic Udic Paleustalf	15.8	UD	0.39	6.1	1.61
Blanket (Ap)	0–13	Clayey smectitic, thermic Pachic Argiustoll	21.1	3	1.75	7.9	1.49
Purves (Ap)	0–6	Clayey smectitic, thermic Lithic Haplustoll	29.3	40	2.49	8	1.26
Genola (Ap1)	0–5	Fine-silty, mixed, calcareous, mesic Typic Calcixerept	45.1	34	3.67	8.1	1.23
Genola (Ap2)	5–18	Fine-silty, mixed, calcareous, mesic Typic Calcixerept	45.8	33	1.65	8.5	1.46
Greenson (Ap1)	0–5	Fine-silty, mixed, superactive, mesic Oxyaquic Calcixeroll	19.2	3	2.94	7.4	1.23
Greenson (Ap2)	5–23	Fine-silty, mixed, superactive, mesic Oxyaquic Calcixeroll	20.9	2	1.88	7.8	1.52
Layton (Ap1)	0–5	Sandy, mixed, superactive, mesic, Oxyaquic Haploxeroll	6	1	0.75	8.2	1.66
Layton (Ap2)	5–25	Sandy, mixed, superactive, mesic, Oxyaquic Haploxeroll	4.7	1	0.66	8.1	1.57
Layton (Ap3)	25–41	Sandy, mixed, superactive, mesic, Oxyaquic Haploxeroll	4.9	1	0.44	8.1	1.64

UD, undetected; OC, organic carbon; BD, bulk density.

Water-soluble P (Soil Survey Staff 1996), Olsen (Olsen et al. 1954), Bray1 (Bray and Kurtz 1945), and Mehlich3 (Mehlich 1984) were measured in soils. Anion exchange resin (AER) extractable P was determined by the method described by Elrashidi et al. (2003a). The AER method is outlined in three sections (soil extraction, P removal from resin, and P measurement) as follows:

Soil Extraction

1. Add 2.0 g of air-dried soil sample (<2 mm) and 100 mL of distilled water to a wide-mouth 250-mL polyethylene bottle. Use at least two replicates for each soil sample in addition to a blank treatment where all steps of the extraction process are performed in the absence of soil.
2. Place a resin bag (containing 4.0 g of air-dried AER- HCO_3) in each bottle. The bottle is mounted horizontally on a reciprocating shaker (displacement = 4.0 cm, and speed = 100 epm) and shaken for an hour at room temperature ($20 \pm 2^\circ\text{C}$). After shaking, remove retained P from resin as described below.
3. Repeat Step 2 above for a 24-h shaking period. The length of individual shaking period is determined in reference to the beginning of first shaking period at time = 0.

Phosphorus Removal from Resin

1. Lift the resin bag out of the soil suspension and wait for 2 min to drain free water. Rinse the bag with a known volume of d.w. (i.e., 5.0 mL) to remove attached soil particles. Add rinsing water to the soil suspension, and keep the soil suspension (when it is necessary) for next extraction.
2. Place the resin bag in a wide-mouth 125-mL polyethylene bottle containing 50 mL of 1.0 M NaCl solution and shake the bottle horizontally in reciprocating shaker (displacement = 4.0 cm, and speed = 100 epm) for 1 h at room temperature.
3. Transfer the NaCl solution to 60-mL polyethylene bottle and add 2.0 mL of concentrated HCl to each bottle.

Phosphorus Measurement

Determine P concentration ($\mu\text{g/mL}$) in an acidified 1.0 M NaCl solution by the modified phospho-molybdate/ascorbic acid method (Olsen and Sommers 1982) or by inductively coupled plasma-optical emission spectrometry (ICP-OES) (Soltanpour et al. 1982).

Phosphorus extracted by Olsen, Bray1, Mehlich3, water, and AER methods (mg/kg) in the control and manure treatments for soils are presented in Table 2.

Table 2. Effect of manure application on P extracted by different methods^a (mg/kg soil) for 12 Texas and Utah surface and subsurface soils

Soil (horizon)	Treatment	Olsen	Bray1	Mehlich3	Water	AER-1h	AER-24h
(mg/kg)							
Maloterra (Ap)	Control	3.35 (1.18)	1.95 (0.21)	11.2 (1.18)	0.46 (0.03)	3.44 (0.27)	10.4 (1.56)
Maloterra (Ap)	Manure	336 (6.93)	102 (4.17)	566 (4.93)	34.0 (0.69)	157 (5.38)	491 (9.27)
Windthorst-1 (Ap1)	Control	16.8 (0.57)	39.0 (0.35)	41.5 (2.53)	3.09 (0.23)	10.9 (1.24)	23.8 (0.45)
Windthorst-1 (Ap1)	Manure	155 (0.38)	267 (5.44)	269 (9.90)	20.0 (0.33)	135 (3.92)	227 (1.19)
Windthorst-1 (Ap2)	Control	1.25 (0.21)	5.05 (0.21)	7.54 (0.24)	0.96 (0.89)	2.06 (0.14)	6.27 (0.11)
Windthorst-1 (Ap2)	Manure	161 (1.06)	269 (11.3)	260 (7.62)	19.9 (0.39)	125 (4.00)	232 (5.87)
Blanket (Ap)	Control	10.5 (0.69)	17.6 (0.49)	21.6 (0.86)	3.68 (0.04)	6.98 (0.23)	13.9 (0.45)
Blanket (Ap)	Manure	404 (2.88)	369 (18.5)	385 (8.11)	49.0 (0.77)	203 (19.4)	502 (1.76)
Purves (Ap)	Control	3.62 (0.13)	0.14 (0.00)	2.47 (0.61)	0.51 (0.06)	2.28 (0.11)	4.26 (0.16)
Purves (Ap)	Manure	262 (4.43)	25.4 (0.43)	333 (13.50)	17.3 (0.33)	134 (25.7)	388 (11.70)
Genola (Ap1)	Control	23.6 (1.27)	2.70 (0.28)	58.3 (3.24)	8.17 (0.10)	28.1 (0.54)	49.8 (1.59)
Genola (Ap1)	Manure	225 (0.21)	63.2 (4.88)	336 (12.39)	32.7 (0.08)	172 (8.77)	358 (6.08)
Genola (Ap2)	Control	3.70 (0.14)	0.85 (0.21)	17.7 (2.20)	4.32 (0.03)	9.47 (0.40)	11.5 (0.13)
Genola (Ap2)	Manure	28.8 (0.78)	0.80 (0.14)	63.0 (1.71)	35.8 (1.20)	32.8 (1.34)	54.5 (0.57)
Greenson (Ap1)	Control	79.7 (0.85)	111 (1.56)	188 (0.61)	6.65 (0.11)	106 (0.87)	172 (1.9)
Greenson (Ap1)	Manure	115 (1.91)	142 (1.56)	232 (3.66)	36.9 (0.41)	143 (4.57)	218 (4.72)
Greenson (Ap2)	Control	26.7 (0.00)	48.0 (0.14)	91.6 (1.42)	9.34 (0.04)	40.9 (1.10)	71.6 (0.51)
Greenson (Ap2)	Manure	76.8 (0.42)	105 (1.70)	156 (6.01)	31.1 (0.53)	106 (4.38)	158 (1.94)
Layton (Ap1)	Control	13.5 (0.07)	28.0 (0.49)	44.8 (0.76)	4.94 (0.05)	19.0 (1.07)	33.2 (1.36)
Layton (Ap1)	Manure	136 (9.76)	193 (0.42)	274 (11.02)	27.7 (1.82)	114 (2.76)	213 (3.29)
Layton (Ap2)	Control	14.9 (1.13)	28.6 (1.56)	44.1 (0.13)	5.08 (0.07)	17.7 (0.15)	32.3 (3.31)
Layton (Ap2)	Manure	138 (8.77)	202 (2.47)	255 (24.89)	26.6 (1.53)	164 (4.24)	285 (2.33)
Layton (Ap3)	Control	18.6 (1.06)	33.2 (0.57)	48.0 (0.19)	5.15 (0.01)	20.1 (0.18)	34.5 (0.12)
Layton (Ap3)	Manure	123 (7.35)	177 (0.21)	245 (2.49)	28.3 (0.10)	94.3 (2.23)	184 (4.40)

^aPhosphorus data in columns are averages followed by standard deviations between parenthesis.

Phosphorus Release Characteristics (PRC)

Implementing the linear relationship between P released from soil by AER (mg/kg soil) and the logarithm of extraction period (h), Elrashidi et al. (2003a) proposed two equations to describe PRC for a soil. For the 1- to 48-h extraction region, the regression equation could be written as follows:

$$P = I + S_2 \times \text{Log } h \quad (1)$$

where P is P released (mg/kg soil), I is intercept (mg P/kg soil), S₂, is slope, and h is extraction period in hours. For the 1- to 60-min extraction region, the regression equation is written as follows:

$$P = I + (I \div 1.78) \times \text{Log } h \quad (2)$$

where $(I \div 1.78) = \text{slope } (S_1)$

In this study, the AER technique was applied to estimate the PRC for soils. For both the control and amended soils, the linear regression equations developed to describe P released for the 1- to 60-min, and 1- to 48-h extraction region are given in Table 3.

Estimation of Runoff Water

Soil Conservation Service (USDA 1991) developed the runoff equation to estimate runoff water from small watersheds by rainfall. The runoff equation is:

$$Q = \{R - [(200 - 2CN)/CN]\}^2 \div \{R + [(800 - 8CN)/CN]\} \quad (3)$$

where, Q is runoff (inches), R is effective rainfall (inches), and CN is curve number, which is dependent on both the hydrologic soil group and type of land cover (i.e., fallow, crop, or grass).

The annual rainfall at any soil location (county, state) was taken from the U.S. National Water and Climate Center (2003). In Eq. (3), the effective rainfall (R) is the portion of annual rainfall that could generate runoff, and it was assumed to be 20% of the annual rainfall. The hydrologic group for soil and related CN numbers for various types of land cover are published in NRCS National Engineering Field Manual (USDA 1991).

For each test plot, the effective rainfall (R) and the runoff curve numbers were determined, and the runoff equation was used to estimate the runoff water (Q) for soil under fallow, crop, and grass. The equation calculated runoff water in inches, and values should be converted to millimeters for this study.

Table 3. Effect of manure application on linear regression equations^a used to predict P released by an anion exchange resin (AER) for 1- to 60-min and 1- to 48-h extraction region in 12 Texas and Utah surface and subsurface soils

Soil	Treatment	Intercept (I) (mg P/kg soil)	Slope (S1) (1–60 min)	Slope (S2) (1–48 h)
Maloterra (Ap)	Control	3.44	1.93	5.05
Maloterra (Ap)	Manure	157.2	88.41	241.8
Windthorst-1 (Ap1)	Control	10.85	6.11	9.39
Windthorst-1 (Ap1)	Manure	134.9	75.88	66.36
Windthorst-1 (Ap2)	Control	2.06	1.16	3.05
Windthorst-1 (Ap2)	Manure	125.2	70.42	77.31
Blanket(Ap)	Control	6.98	3.92	5.05
Blanket(Ap)	Manure	203.1	114.1	216.5
Purves(Ap)	Control	2.28	1.28	1.44
Purves(Ap)	Manure	124.6	70.09	190.5
Genola (Ap1)	Control	28.08	15.79	15.77
Genola (Ap1)	Manure	172.4	96.97	134.2
Genola (Ap2)	Control	9.47	5.32	1.49
Genola (Ap2)	Manure	32.81	18.45	15.71
Greenson (Ap1)	Control	106.2	59.73	47.45
Greenson (Ap1)	Manure	143.1	80.44	54.22
Greenson (Ap2)	Control	40.92	23.01	22.21
Greenson (Ap2)	Manure	105.7	59.45	37.56
Layton (Ap1)	Control	19.01	10.69	10.31
Layton (Ap1)	Manure	114.1	64.12	72.03
Layton (Ap2)	Control	17.73	9.97	10.58
Layton (Ap2)	Manure	163.49	91.94	88.06
Layton (Ap3)	Control	20.12	11.32	10.38
Layton (Ap3)	Manure	94.28	53.02	65.15

^a $P = I + S1 \times (\log h)$ for 1- to 60-min, and $P = I + S2 \times (\log h)$ for 1- to 48-h extraction region.

Estimation of Runoff Phosphorus

Various forms of P like moisture are held by soil particles at different energy levels. Kinetic energy exerted by raindrops on surface soil plays a major role in releasing P. The Soil Survey Laboratory developed the AER method to determine PRC for soils (Elrashidi et al. 2003a). In this method, different levels of energy are applied by water on soil particles when soil suspension is shaken for various periods of time at a constant speed. Understanding the relationship between shaking and rainfall energy enabled the prediction of P released from surface soil by rainfall of known intensity and duration.

Assuming a rainfall intensity of 50 mm/h and that rain force affects the top 10-mm layer of soil, a conversion factor (shaking energy/rainfall energy) = 15.9 was calculated. Under the experimental conditions, an energy applied by 3.8 min of shaking the soil suspension was equivalent to an hour of rainfall event of intensity of 50 mm/h.

In this study, we used a conversion factor of 15 to calculate the shaking period (h) equivalent to the annual rainfall. The log of the calculated shaking period was applied in the respective regression equation (Table 3) to estimate the amount of P released from soil by the annual rainfall (mg/kg soil). The values of annual rainfall (mm), runoff water (mm), and the amount of P released (mg/kg soil) were used to estimate 1) fraction of released P which was removed from surface soil by runoff water (runoff P) and 2) fraction of released P which remained in soil after runoff events (available P). With the knowledge of soil bulk density and assumption that P was released from the top 10-mm soil by the annual rainfall, both the runoff and available P could be expressed as kg/ha/yr.

RESULTS AND DISCUSSION

Effect of Manure on Extractable Soil Phosphorus

We used three traditional chemical extractions of P, in addition to water and AER method to evaluate the effect of manure application on soil P. Identification of P forms extracted by these methods can help to perform better evaluation. Sodium bicarbonate/hydroxide solution (Olsen) can remove water-soluble, adsorbed P and relatively soluble Ca-, Al-, and Fe-phosphate minerals (Olsen and Sommers 1982). Bray1 (a combination of hydrochloric acid and ammonium fluoride) and Mehlich3 [a combination of acids (acetic and nitric), salts (ammonium fluoride and ammonium nitrate), and the chelating agent ethylenediaminetetraacetic acid (EDTA)] are aggressive extractions particularly in acid and near neutral soil environment where they can dissolve large amounts of Ca-, Al-, and Fe-phosphates in addition to water-soluble and adsorbed P forms. Actually, Olsen extraction removes P from relatively soluble P minerals compared with Bray1 and Mehlich3, which can attack P minerals of much lower solubility (Elrashidi et al. 2003b).

Except for Greenon, P extracted from untreated surface soils (Ap1) ranged between 3.35 and 23.6 (Olsen), 0.85 and 39.0 (Bray1), and 11.2 and 58.3 mg/kg (Mehlich3). Greenon soil appeared to have a relatively higher P content than other soils as 80, 111, and 188 mg P/kg was extracted by Olsen, Bray1, and Mehlich3 methods, respectively.

Only a small amount of water-soluble P was present in untreated soils, ranging between 0.46 and 3.68 mg/kg for Texas soils and between 4.32 and 9.34 mg/kg for Utah soils. The AER-1h-P is mainly derived from water-soluble and adsorbed P forms (Elrashidi et al. 2003a). Phosphorus extracted

by AER-1h suggested that all soils (except Greenston) contained relatively small amounts of adsorbed P. The least P amount was found in Purves (1.8 mg/kg), whereas Genola contained the highest value (19.9 mg/kg). Greenston soil, however, had approximately 100 mg/kg of adsorbed P.

For Texas and Utah soils, AER-1h-P showed a highly significant correlation with water-P (0.841), Olsen-P (0.882), Bray1-P (0.752), and Mehlich3-P (0.923). The AER-1h-P could be considered a good index for readily available P forms in soils (Elrashidi et al. 2003a).

Table 2 shows that the AER-24h extraction could remove all P forms dissolved by Olsen, Bray1, and Mehlich3 solutions. A highly significant correlation was observed between P determined by AER-24h method and P removed by Olsen (0.974), Bray1 (0.672), and Mehlich3 (0.948). Similar data were reported for 24 U.S. benchmark soils (Elrashidi et al. 2003a). Thus, the AER-24h-P could be considered a good measure of the quantity of available P present in soil. Olsen and Khasawneh (1980) reported that AER-P was related to labile P and it could be a valid measure of the quantity factor for soils.

Application of manure on surface soils increased considerably the amount of P extracted by all methods (Table 2 and Figures 1–3). For example, water-P increased in the Windthorst soil from 3.1 to 20.0, AER-1h-P from 10.9 to 134.9, AER-24h-P from 23.9 to 226.5, Olsen-P from 16.8 to 154.6, Bray1-P from 39.0 to 266.7, and Mehlich3 from 41.5 to 269.4 mg/kg soil. These results indicated that the three chemical extractions (Olsen, Bray1, and Mehlich3) along with the water and AER method proved to be good indices for evaluating the effect of manure application on soil P. Other investigators (Pote et al. 1996; Sauer et al. 2000; Gaston et al. 2003) applied chemical extractions (i.e., Olsen, Bray1, and Mehlich3) successfully to study the effect of manure application on extractable P for soils.

The AER method, however, applies water in the extraction, which simulates natural field conditions for agronomic or environmental P consideration. Furthermore, the AER method can measure both the availability and quantity of P for soil in addition to the rate of P release (Amer et al. 1955). Recently, the AER method was applied to quantify both the available and runoff P for agricultural land (Elrashidi et al. 2003a). Accordingly, the AER method could provide a better tool in evaluating the effect of manure application on soil P than chemical extractions. Our discussion in this report will be mainly focused on data derived from the AER method and water extraction, which simulates natural field conditions.

Downward Movement of Phosphorus

The downward movement of manure-P was investigated in the Texas soil (Windthorst) and three Utah soils (Genola, Greenston, and Layton). Results obtained from all extraction methods (Table 2 and Figure 3) show a

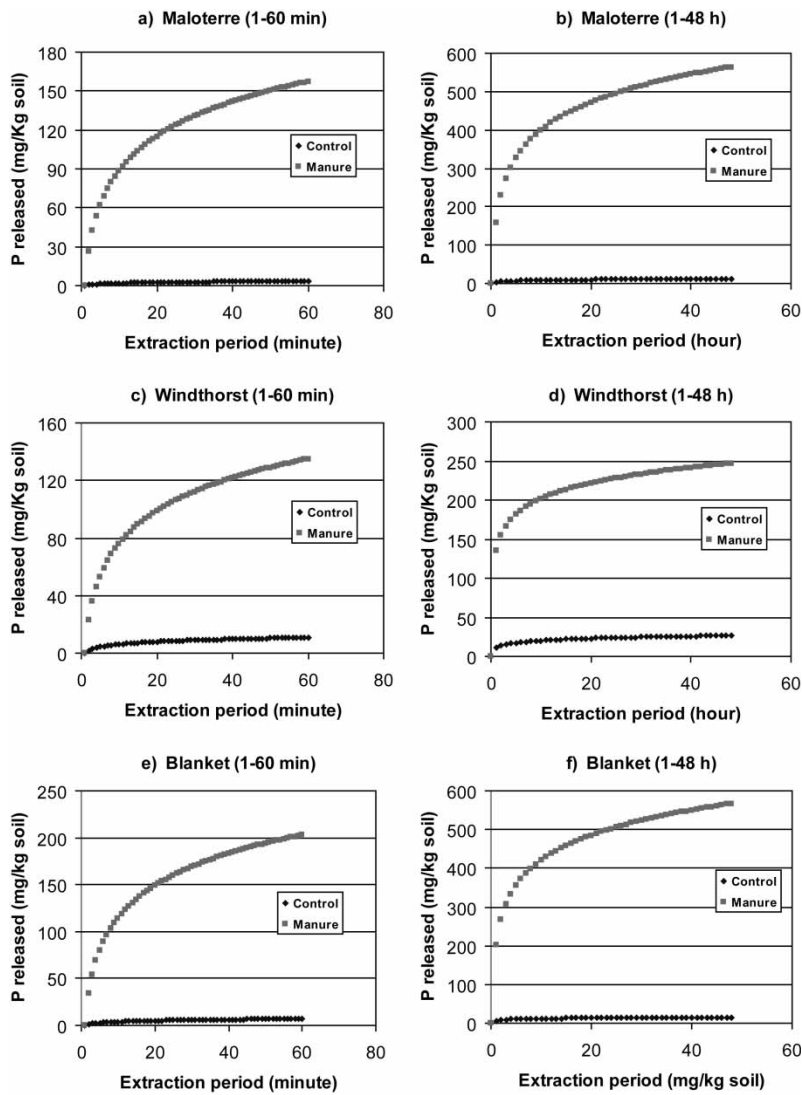


Figure 1. Effect of manure application on phosphorus release characteristics (1- to 60-min and 1- to 48-h region) for three Texas surface soils.

considerable downward movement for manure-P applied to Windthorst, Greenson, and Layton soil.

For example, manure application in the Windthorst soil enhanced the downward movement of water-soluble P and that extracted mainly from adsorbed (AER-1h-P) and mineral phosphates (AER-24h-P). The water-P, AER-1h-P, and AER-24h-P increased by a magnitude of 18.9, 123.1, and 225.6 mg/kg soil, respectively in the Ap2 horizon. For the light-textured

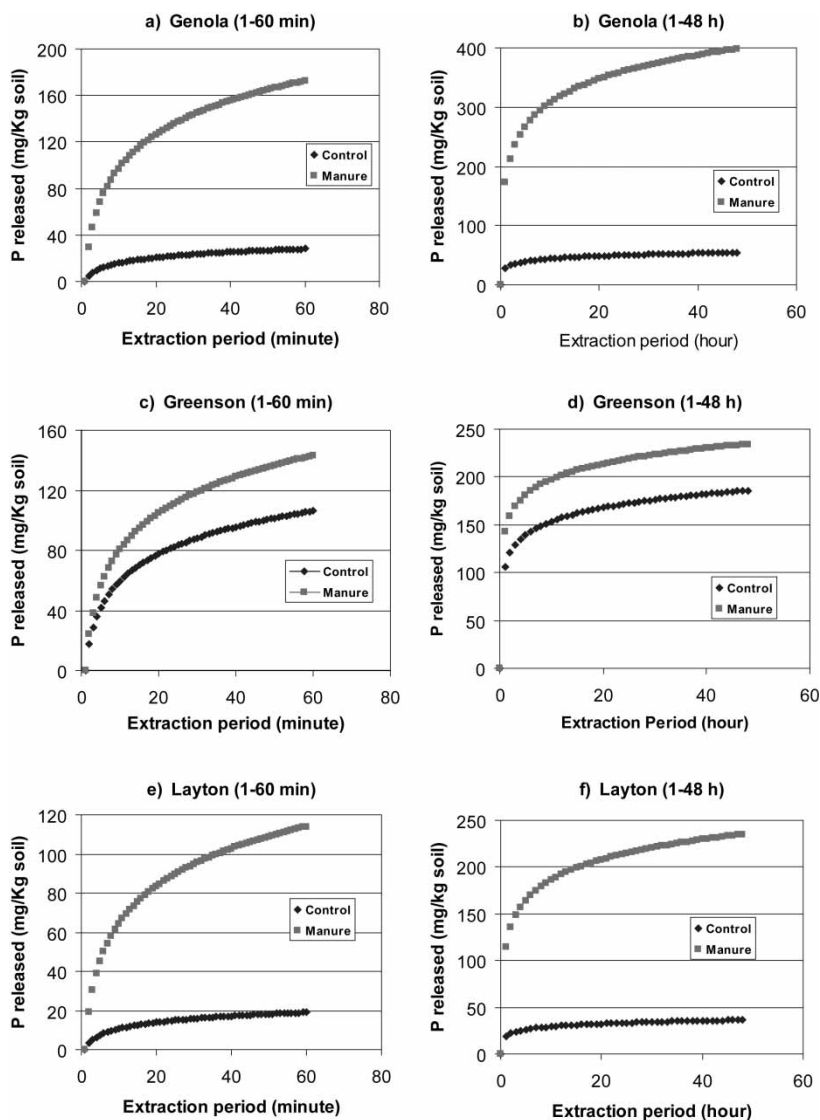


Figure 2. Effect of manure application on phosphorus release characteristics (1- to 60-min and 1- to 48-h region) for three Utah surface soils.

soil (Layton), which had a low clay (5–6%) and CaCO_3 (1%) content, the manure-P could move deep into the Ap3 horizon (Figure 3). James et al. (1996) investigated P mobility in Utah calcareous soils under heavy manure application and found that manure-P affected subsoil layers as deep as 210 cm, evidently reflecting the mobility of organic P. In long-term manure-amended soils, Kuo and Baker (1982) reported P downward movement

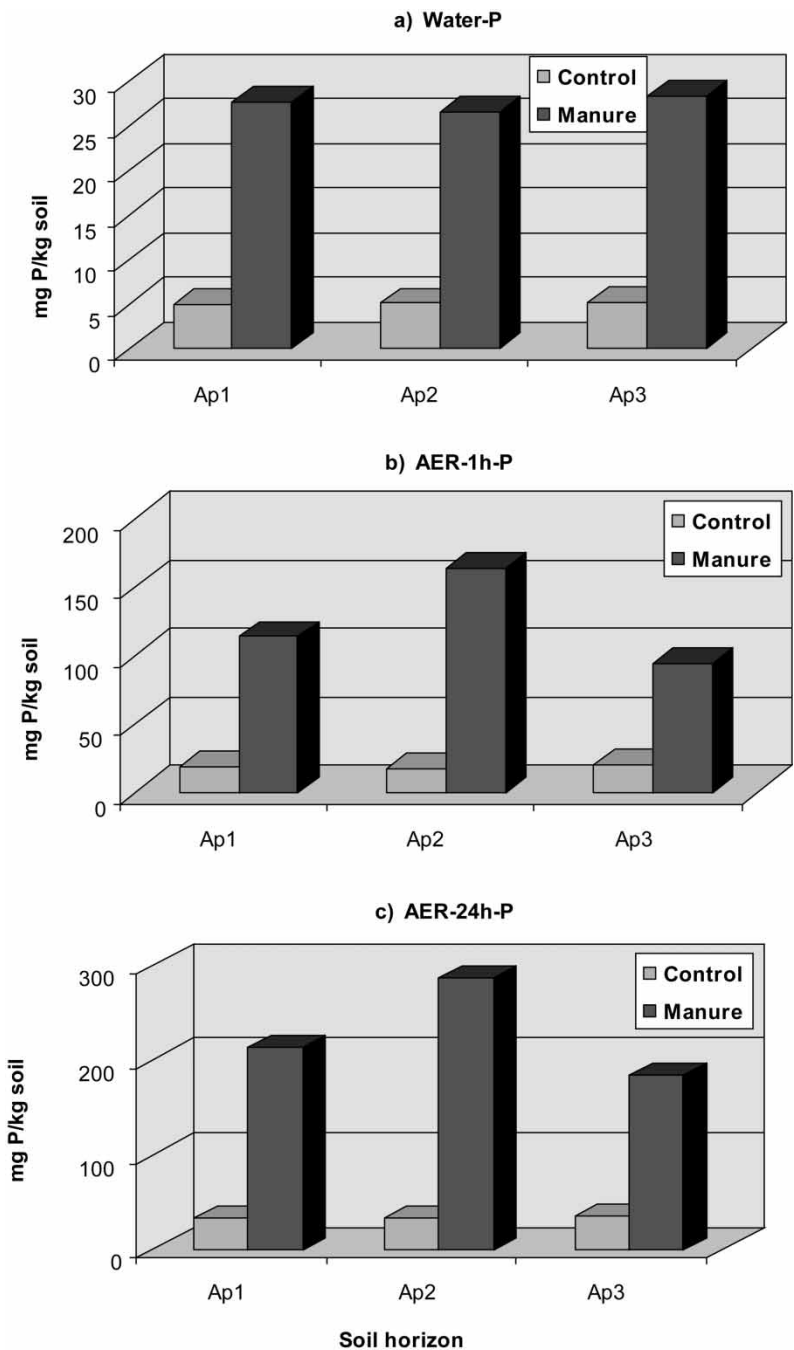


Figure 3. Effect of manure application on water-P (a), AER-1h-P (b), and AER-24h-P (c) in Ap1, Ap2, and Ap3 horizon (mg/kg soil) for Layton soil.

below the surface 20-cm layer. Campbell and Racz (1975) showed elevated levels of P at 120–150 cm in a calcareous soil below a beef cattle feed lot.

For the Genola soil, the data (Table 2 and Figure 4) suggested a downward movement of the water-P, whereas a very limited movement was observed for the AER-extractable P (AER-1h-P and AER-24h-P). The water-P is present in anionic forms (i.e., H_2PO_4^- and HPO_4^{2-}), which can move even in standing water by diffusion (Lindsay 1979). On the other hand, P mainly associated with adsorbed forms (AER-1h-P) and those released from P minerals (AER-24h-P) were mobile in the light-textured soils (Windthorst, Greenon, and Layton). But these P forms were somewhat immobile in the Genola soil, which had very high clay, and CaCO_3 content that could limit water flow.

It is well established that the mobility of organic and inorganic colloids plays a major role in soil formation and pedogenic processes (Birkeland 1984). For surface soils amended with manure, both adsorbed and mineral P forms extracted by the AER method are attached to the colloidal organic and inorganic particles, which can move downward with water flow. These colloidal P particles can be mobile in light-textured soils where water movement is evident. In a study on Florida sandy soils amended with manure, Elrashidi et al. (2001) reported a downward movement of P through the soil profile into the saturated zone at a depth of 180–240 cm. They concluded that colloidal Al-phosphates accumulated in the topsoil could move down through the sandy soil profile. On the contrary, the mobility of these colloidal P particles can be limited in a heavy-textured soil such as Genola.

Phosphorus Release Characteristics (PRC)

Figures 1 and 2 show the relationship between AER extraction periods and P released for three Texas and three Utah surface soils, respectively. A similar relationship was obtained for other soils (not shown).

Phosphorus released by the AER at three extraction periods was used: AER-4min, AER-1h, and AER-24h to investigate changes in the PRC of soil as a result of manure application. The AER-4min-P is equivalent to the amount of P released from surface soil by an hour of rainfall of 50 mm/h intensity. The AER-1h-P represents mainly the readily available P (i.e., water-soluble and adsorbed P), whereas the AER-24h-P can be a good measurement of the quantity of available P for soil.

Following the 1st h of AER extraction, the P release rate decreased significantly because only sparingly soluble minerals can release P into solution. For Windthorst surface soil as an example, P release rate was 10.8 mg/h at the 1st h of extraction and dropped to 2.83 mg/h at the 2nd h (Figure 5). Then the release rate decreased with time and leveled off (0.086 mg P/h) at the 48-h extraction period. Similar results were obtained for other soils (not shown).

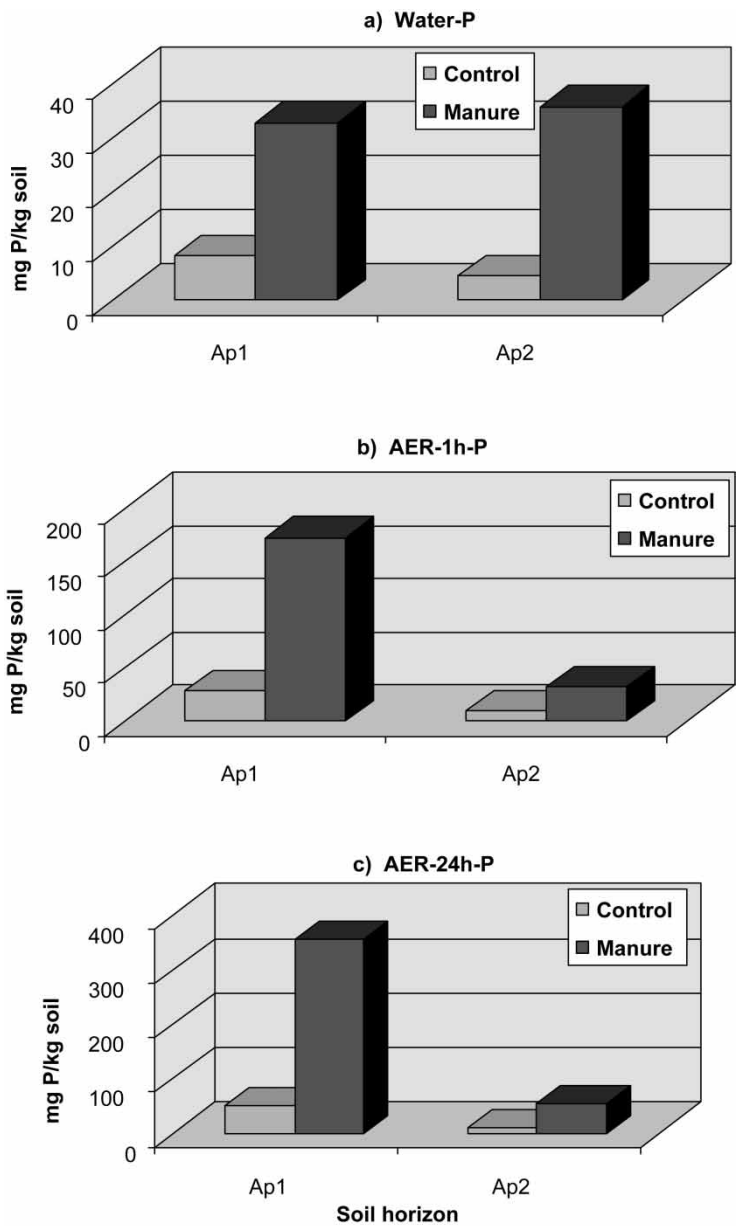


Figure 4. Effect of manure application on water-P (a), AER-1h-P (b), and AER-24h-P (c) in Ap1 and Ap2 horizon (mg/kg soil) for Genola soil.

The rate of P release approaches zero only when all P minerals in the soil are dissolved completely, which is unlikely under the experimental conditions. The dissolution process might take several months because of the extremely

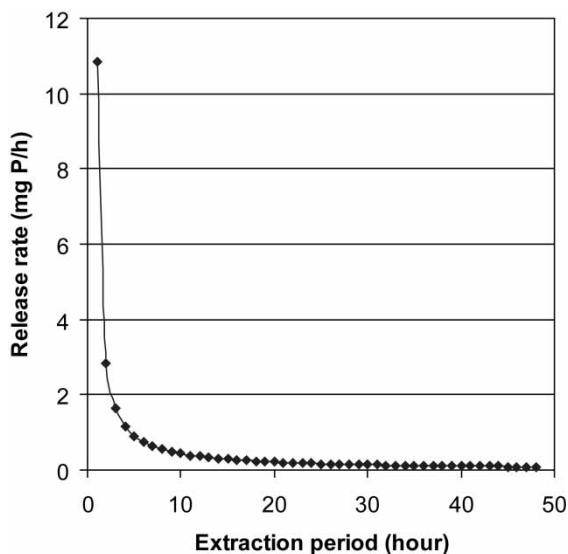


Figure 5. Effect of extraction period (h) on P release rate (mg/h) for Windthorst surface soil.

low solubility of some P minerals (i.e., fluorapatite, strengite, and variscite) (Lindsay 1979). Accordingly, it was assumed that the amount of P released had approached a maximum at 48-h extraction period and could represent the P capacity for soil.

For Texas soils, the averages of AER-4 min-, AER-1 h-, and AER-24 h-P were 1.73, 5.13, and 11.7 mg/kg soil, which accounted for 13.0, 38.3, and 89.0% of the soil P capacity (AER-48 h-P), respectively. The application of manure increased the respective P concentrations to 50.4, 149.0, and 367.7 mg/kg soil, but it appeared not to change much the percentage value of P release. For manure-amended soils, the averages of AER-4 min-, AER-1 h-, and AER-24 h-P were 13.2, 39.1, and 89.1% of the soil P capacity, respectively.

For Utah soils, the application of manure increased considerably the amount of P released from soil by the AER at AER-4 min, AER-1 h, and AER-24 h extraction periods. Similar P release patterns were observed for the control and amended soils where the respective averages were 19.1 and 17.8% for AER-4 min-P, 56.5 and 52.8% for AER-1 h-P, and 92.2 and 91.6% of the soil P capacity for AER-24 h-P.

Effect of Manure on Runoff Phosphorus

As mentioned in Materials and Methods, we applied the runoff equation to estimate runoff water for the three Texas and four Utah surface soils (Ap1

horizon) under hypothetical land cover (fallow, crop, and grass). The location (county, state), annual rainfall, hydrologic group, and the estimated runoff water (mm/yr) for the seven surface soils under these land covers are given in Table 4.

For the four Texas soils that are located in Erath County (annual rainfall of 809 mm/yr), the average runoff water was 17.3% of annual rainfall for fallow, 15.8% for crop, and 13.2% for grass. These averages were in

Table 4. Location, annual rainfall, hydrologic group, and estimated surface runoff water (mm/yr)^a for seven Texas and Utah surface soils amended with manure under different types of land cover

Soil	Treatment	Location (county/ state)	Hydrologic group	Rainfall	Surface runoff ^a		
					Fallow	Crop	Grass
					(mm/yr)		
Maloterre (Ap)	Control	Erath, TX	D	809	144	132	115
Maloterra (Ap)	Manure	Erath, TX	D	809	144	132	115
Windthorst (Ap1)	Control	Erath, TX	C	809	135	124	102
Windthorst (Ap1)	Manure	Erath, TX	C	809	135	124	102
Blanket (Ap)	Control	Erath, TX	C	809	135	124	102
Blanket (Ap)	Manure	Erath, TX	C	809	135	124	102
Purves (Ap)	Control	Erath, TX	D	809	144	132	115
Purves (Ap)	Manure	Erath, TX	D	809	144	132	115
Genola (Ap1)	Control	Sanpete, UT	B	301	29	143 ^b	9
Genola (Ap1)	Manure	Sanpete, UT	B	301	29	143 ^b	9
Greenson (Ap1)	Control	Cache, UT	C	450	66	164 ^b	41
Greenson (Ap1)	Manure	Cache, UT	C	450	66	164 ^b	41
Layton (Ap1)	Control	Weber, UT	A	334	21	113 ^b	1
Layton (Ap1)	Manure	Weber, UT	A	334	21	113 ^b	1

^aSurface runoff water (mm/yr) was estimated by the NRCS runoff equation ([USDA 1991]).

^bSprinkler irrigation of 715, 566, and 682 (mm) was added to the annual rainfall to estimate the surface runoff water for Genola, Greenson, and Layton soil under crop cover, respectively.

agreement with those reported for 13 U.S. benchmark soils in areas where rainfall was greater than 800 mm/yr (Elrashidi et al. 2003a). The three Utah soils are located in an arid region (rainfall ranges from 300 to 450 mm/yr), a supplemental surface irrigation is usually required during crop growth season. Thus, a sprinkler irrigation of 715, 566, and 682 mm was added to the annual rainfall to estimate the runoff water for Genola, Greenson, and Layton soil under crop cover, respectively. The estimated average of runoff water was 10.2, 13.8, and 4.0% of the annual rainfall for fallow, crop, and grass, respectively.

The regression equations used to predict the amount of P released from soils (Table 3) along with the estimated runoff water and annual rainfall (Table 4) were applied to predict: 1) P released from soil by annual rainfall (mg/kg soil), 2) runoff P (kg/ha/yr), and 3) available P (kg/ha/yr) for soils under fallow, grass, and crop. The results for untreated and manured surface soils are given in Table 5.

For control Texas soils, the amount of P released from surface soil by rainfall ranged between 2.32 and 11.1 mg/kg soil, which is equivalent to 0.29–1.67 kg/ha/yr. For soils under fallow, crop, and grass, only a small portion averaging 17.3, 15.6, and 13.0% of the released P, respectively, was removed by runoff water. Thus, most of the released P remained in soils (available P) after runoff event, and it ranged between 0.24 and 1.46 kg/ha/yr. The data, in general, reflected very low soil P content, which had a minor impact on the runoff P and water quality.

Application of manure increased soil P considerably and the amount of P released from surface soil by rainfall, which increased the runoff P and available P. For Texas soils, the highest response was observed for Blanket soil where the released P increased by 29-fold, from 7.11 to 206.7 mg/kg soil, which is equivalent to 1.06–30.8 kg/ha/yr. Consequently, the runoff P increased from 0.18 to 5.15 kg/ha/yr for fallow, from 0.16 to 4.71 kg/ha/yr for crop, and from 0.13 to 3.88 kg/ha/yr for grass. The available P increased from 0.88, 0.90, and 0.93 kg/ha/yr to 25.7, 26.1, and 26.9 kg/ha/yr for fallow, crop, and grass, respectively. Slightly lower effects of manure application on the released P and both the runoff, and available P were noticed for other Texas soils (Table 5).

As expected, Utah cropland where surface irrigation was used during the growing season showed higher values for the released P than fallow or grassland. Furthermore, the application of manure increased considerably the amount of P released, which was reflected on both the runoff P and available P. For example, the application of manure in the Genola soil increased the released P from 30.2 to 185.2 mg/kg soil (3.71–22.8 kg/ha/yr) for crop, and from 21.8 to 134.0 mg/kg soil (2.68 to 16.5 kg/ha/yr) for fallow and grass. The runoff P increased from 0.26 to 1.58 kg/ha/yr for fallow, from 0.52 to 3.20 kg/ha/yr for crop, and from 0.08 to 0.50 kg/ha/yr for grass. The available P increased from 2.43, 3.19, and 2.60 kg/ha/yr to 14.9, 19.6, and 16.0 kg/ha/yr for fallow, crop, and grass, respectively.

Table 5. Effect of manure application on released^a, runoff,^b and available^c phosphorus (kg/ha/yr) for seven Texas and Utah surface soils under fallow, grass, and crop land cover

Soil	Treatment	Released P ^a (mg/kg soil)		Runoff-P ^b (kg/ha/yr)			Available-P ^c (kg/ha/yr)		
		Fallow/Grass	Crop	Fallow	Crop	Grass	Fallow	Crop	Grass
Maloterre (Ap)	Control	3.50	3.50	0.09	0.08	0.07	0.40	0.41	0.42
Maloterra (Ap)	Manure	160.12	160.12	3.99	3.66	3.20	18.43	18.75	19.22
Windthorst (Ap1)	Control	11.05	11.05	0.28	0.26	0.21	1.39	1.41	1.46
Windthorst (Ap1)	Manure	137.43	137.43	3.10	2.84	2.34	15.45	15.71	16.22
Blanket (Ap)	Control	7.11	7.11	0.18	0.16	0.13	0.88	0.90	0.93
Blanket (Ap)	Manure	206.74	206.74	5.15	4.71	3.88	25.66	26.09	26.92
Purves (Ap)	Control	2.32	2.32	0.05	0.05	0.04	0.24	0.24	0.25
Purves (Ap)	Manure	126.94	126.94	2.84	2.61	2.28	13.15	13.38	13.71
Genola (Ap1)	Control	21.81	30.16	0.26	0.52	0.08	2.43	3.19	2.60
Genola (Ap1)	Manure	133.95	185.22	1.58	3.20	0.50	14.89	19.59	15.97
Greenson (Ap1)	Control	92.99	114.09	1.67	2.26	1.03	9.77	11.77	10.40
Greenson (Ap1)	Manure	125.22	153.64	2.25	3.05	1.39	13.16	15.85	14.01
Layton (Ap1)	Control	15.25	20.41	0.16	0.38	0.01	2.37	3.01	2.53
Layton (Ap1)	Manure	91.46	122.46	0.95	2.27	0.03	14.23	18.06	15.15

^aReleased P, phosphorus released from surface soil by annual rainfall and irrigation.^bRunoff P, the fraction of released phosphorus that is removed by runoff water.^cAvailable P, the fraction of released phosphorus remained in soil after runoff events.

In this study, the amount of P removed from manured soils by annual rainfall was generally below the runoff P threshold (5.0 kg/ha/yr), which may pose a risk for surface waters (Elrashidi et al. 2003a), suggesting a low impact on water quality. For these Texas and Utah soils, however, repeated applications of manure on cropland at this relatively high rate (100 Mg/ha) might increase the risk of P pollution for near surface freshwater bodies.

Unfortunately, studies quantifying effects of natural rainfall on the transport of P from manured fields are scarce in the literature. Most studies, however, applied simulated rainfall for small field plots. At the Iowa Agricultural Experimental Station, Tabbara (2003) applied a rainfall simulation (63.5 mm/h for 1.5 h) on field plots (Terril loam soil) that received two applications of liquid swine manure 24 h before. For these field plots, the mean P losses by runoff varied from 0.4 to 1.7 kg/ha as dissolved reactive P.

Preedy et al. (2001) applied dairy slurry at a rate of 29 kg P/ha to Halls-worth clay soil plots (3 × 10 m) covered with perennial ryegrass at an experimental site in southwest England. In the following 169 h, an application of simulated rainfall of 50 mm/h intensity resulted in removal of 6.2–7.9% of applied P (1.8–2.3 kg P/ha) by surface runoff and subsurface flow. The removed P amounts were equivalent to annual P export reported from grassland in England (Haygarth et al. 1998).

CONCLUSIONS

A technique implementing a routine Soil Survey Laboratory method and USDA runoff equation was applied to predict the effect of manure application on 1) P released from surface soil by rainfall and 2) plant available P and runoff P for soil. The technique uses major source and transport factors affecting runoff P (soil P, soil hydrology, land cover, and rainfall) and can be outlined as follows:

- A routine laboratory AER method is applied to measure P released (mg/kg soil) at 1 and 24 h extraction periods, and then the developed regression equations are used to predict P release characteristics (PRC) for soil.
- A USDA runoff equation is applied to calculate the volume of runoff water (mm) generated by the annual rainfall at the soil location.
- An energy conversion factor, regression equations, and annual rainfall are used to calculate the amount of P released from surface soil by rainfall (kg/ha/yr).
- A ratio of runoff water to annual rainfall is used to calculate the portion of released P, which is removed by runoff water (runoff P), and the portion of released P, which remains in soil after a runoff event (available P).

The technique was applied on seven soils in Texas and Utah. The results showed that manure application could provide substantial amounts of

available P for crop and hay production. The downward movement of manure-P through the soil profile suggested that deep-rooted plants could also benefit from manure application. But repeated manure applications on cropland could lead to P accumulation in the topsoil, which increases the P transported by runoff into near surface waters.

The technique can be applied to predict both the agronomic benefits and environmental impact of manure and/or P fertilizer applications on an agricultural watershed of known soils, area, and land cover. The amount of soil P available for crop production and P removed from topsoil by runoff into near surface freshwater body can be estimated. The information can be useful for planning nutrient and waste management practices.

The climate, soil P, soil hydrology, and land cover are factors considered in estimating the runoff P by this cost-effective technique. It is understood that other factors (i.e., land topography and distance to surface water) might be involved in the transportation process of soil P. When resources are available, such factors could be investigated in a site-specific study.

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